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Two-quasiparticle K-isomers and pairing strengths in the neutron-rich isotopes ^{174}Er and ^{172}Er

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Abstract

Isomeric two-quasiparticle states have been identified in the neutron-rich isotopes ^{172}Er and ^{174}Er using multi-nucleon transfer reactions with ^{136}Xe beams incident on various targets, and γ-ray spectroscopy with Gammasphere. A candidate for the $K^\pi = 6^+$ two-quasineutron state in ^{172}Er is found at 1500 keV. In ^{174}Er, a nuclide whose level scheme was previously unknown, a long-lived isomer is identified at 1112 keV decaying via an inhibited E1 transition and revealing the yrast sequence of ^{174}Er. This isomer is proposed to be a $K^\pi = 8^-$ two-quasineutron state, defining a sequence in the $N = 106$ isotones extending from the well-deformed neutron-rich isotope ^{174}Er to the neutron-deficient isotope ^{188}Pb, where the presence of the isomer signifies a prolate minimum in an otherwise spherical well. Configuration-constrained potential-energy surface calculations are used to predict the excitation energies of the 6^+ and 8^- intrinsic states and as a basis for extracting the pairing force strength, G_n, in the $N = 104$ and $N = 106$ isotones.

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A major focus of current research is the study of nuclei close to, or to the neutron-rich side of, the stability line, nuclei which are generally inaccessible through the fusion–evaporation reactions that have provided much of the information on high-spin phenomena in the past. Nevertheless, recent studies have demonstrated the value of inelastic and deep-inelastic reactions with heavy-ion beams, in combination with high-efficiency γ-ray arrays, for probing the spectroscopy of these regions [1]. The presence of isomeric states adds an additional dimension of selectivity, enhancing by orders of magnitude the sensitivity in reactions which usually populate a very broad range of nuclei.

In the well-deformed nuclei near $A \sim 180$, and $Z \sim 72$ the presence close to the Fermi surface of neutrons and protons with relatively high projections (Ω) of the particle angular momentum on the deformation axis, results in an abundance of multi-quasiparticle isomeric states. For lower (and also much higher) proton numbers, the frequency of these isomers is likely to be reduced, however, 2-quasiparticle excitations are still likely to result in isomeric states. Progress in identifying such

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states in neutron-rich nuclei has, however, been essentially incremental since the cross-sections for transferring neutrons diminishes rapidly with the number of transferred particles. As well, such studies have often relied on earlier assignments of excited states (of somewhat lower energy precision) seen in two-neutron transfer reactions on the heaviest stable isotope of a given species. Partly for these reasons, excited states in the even–even Er isotopes have as yet only been extended to ^{172}Er [2] and similarly in the Yb case to ^{178}Yb [3], while in Hf both ^{182}Hf [4] and ^{184}Hf [5] have established yrast levels. In the W isotopes, with ^{186}W as the heaviest stable isotope, only a tentative scheme has been proposed for the first few levels in ^{188}W [6], and an isomeric decay into an yrast sequence has been suggested for ^{190}W [7]. The latter case is from relativistic fragmentation rather than multi-nucleon transfer, a technique which facilitates isotopic identification, but which to date has limited capabilities for the γ–γ coincidence measurements necessary to substantiate the proposed sequence.

In the present work, we have identified excited states in the neutron-rich isotope ^{174}Er, for which no excited states had previously been reported. (A spectrum of γ-rays selected on the isotope ^{174}Er in fragmentation studies has been published, but no transitions were assigned [8].) A long-lived isomer is observed feeding into the proposed 8^+ state of the ground-state rotational band. The isomer can be identified with the $K^\pi = 8^-$ intrinsic state that occurs in the higher-Z, $N = 106$ isotones. An isomer is also established in ^{172}Er which we associate with the corresponding 6^+ isomeric state in the $N = 104$ isotones. The 6^+ and 8^- systematics are compared with potential-energy surface calculations, in the context of the neutron pairing strength. One surprising result is that while the pairing strengths required to reproduce experiment in the $N = 106$ cases are similar to those derived from mass-differences, those in the $N = 104$ cases are not.

Measurements were made using 6.0 MeV per nucleon ^{136}Xe beams provided by the ATLAS Facility at Argonne National Laboratory. The beams were incident on various targets, using a configuration primarily designed for observation of transitions in nuclei which have stopped in the target or backing. In one set of measurements, nanosecond pulses, separated by about 825 ns, were incident on targets of enriched ^{176}Yb approximately 6 mg/cm^2 in thickness with a 25 mg/cm^2 Au foil directly behind. The target thickness was such as to integrate over the main yield of inelastic processes from $\sim$20% above the Coulomb barrier, down to the barrier. Gamma-rays were detected with Gammasphere [12], with 100 detectors in operation.

These experiments complement our earlier measurements on targets of natural Lu (97% ^{175}Lu), Lu enriched in ^{176}Lu, and enriched ^{174}Yb, some results of which have been reported recently [9–11]. Triple coincidences were required with a total of 2×10^9 events recorded in the ^{176}Yb case.

The main data analysis was carried out with γ–γ–γ cubes with various time-difference conditions, and also with time constraints with respect to the pulsed beam to select different out-of-beam regimes (in the 0–800 ns range), exploiting developments in software [13] for efficient analyses.

Fig. 1 shows a set of gamma-ray spectra, with double-coincidence gates as indicated, obtained with the ^{176}Yb target and demanding events between beam pulses. These spectra define a delayed cascade sequence with a rotational spacing, fed by the 163 keV γ-ray. The inset is a corresponding sum of gates. Characteristic Er X-rays are evident, together with the 81.6 keV transition which we propose as the $2^+ \to 0^+$ transition in the even–even nucleus ^{174}Er. Note that the transition energies are close to the ground state band transitions in the target ^{176}Yb which is strongly populated in these measurements. However, as shown in the upper pair of panels of Fig. 1 where transitions in ^{174}Er and ^{176}Yb are compared, the experimental resolution and dispersion is such that the two sequences are clearly separated. These spectra were selected using double gates with the 163 keV line placed in ^{174}Er and an equivalent set gating on the 96 keV E1 transition from the known 8^- isomer in ^{176}Yb.

The population of the new isomer is approximately 1.5% relative to the ^{176}Yb isomer, consistent with two-proton transfer from the target. Since the transition energies do not match the known ^{172}Er ground-state band sequence [3] the only other even–even Er isotope which could be populated would be ^{176}Er, but this would involve the charge exchange reaction which is normally suppressed. Intensity balances for the 163 keV transition assuming (obviously) that the other cascade transitions are pure E2, gives $\alpha_T(163) \leqslant 0.10$ which is only consistent with an E1 multipolarity, supporting the proposed $K^\pi = 8^-$ assignment and therefore, association with the two-quasineutron 8^- isomer known in the $N = 106$ isotones.

As well as the nanosecond-pulsed measurements, a series of measurements using a macroscopically chopped beam with (beam on)/(beam off) conditions of (1 ms)/(3 ms) for the ^{176}Yb target, and with out-of-beam dual coincidence events recorded in reference to a precision clock, was carried out. Gamma–gamma matrices as a function of the time were constructed, allowing long lifetimes to be isolated gated on specific cascades.

The intensity of the proposed cascade in ^{174}Er obtained as a function of time from these measurements, is shown in the left panel of Fig. 2. There is no significant decrease in intensity over the 3 ms period; the dashed line in this figure indicates the decay curve for an 8 ms lifetime which is adopted as a conservative lower limit for the lifetime of the 8^- isomer.

The systematics of the $K^\pi = 8^-$ isomers in the $N = 106$ isotones, incorporating the new scheme for ^{174}Er, is given in Fig. 3.

This shows an extensive sequence of isomers arising from the same 2-quasineutron configuration: $\nu^2\, 7/2^-[514] \otimes 9/2^+[624]$; $K^\pi = 8^-$, with lifetimes ranging from seconds down to microseconds. The isomerism arises from the nature of the E1 decay between the $K^\pi = 8^-$, 2-quasiparticle state and the $K = 0$ ground-state, which has a forbiddenness $\nu = \Delta K - \lambda = 7$, where λ is the multipolarity. The hindrance factor F is given by ratio of the partial mean-lives to the Weisskopf estimates τ_W, so that $F = \frac{\tau}{\tau_W}$. The so-called reduced hindrances $f_\nu = F^{1/\nu}$, are given for the $N = 106$ isotones in the right-hand panel of Fig. 2. They vary from a value of about 100 in ^{176}Yb reducing to $\sim$20 in ^{188}Pb. (Note that this does not include the additional

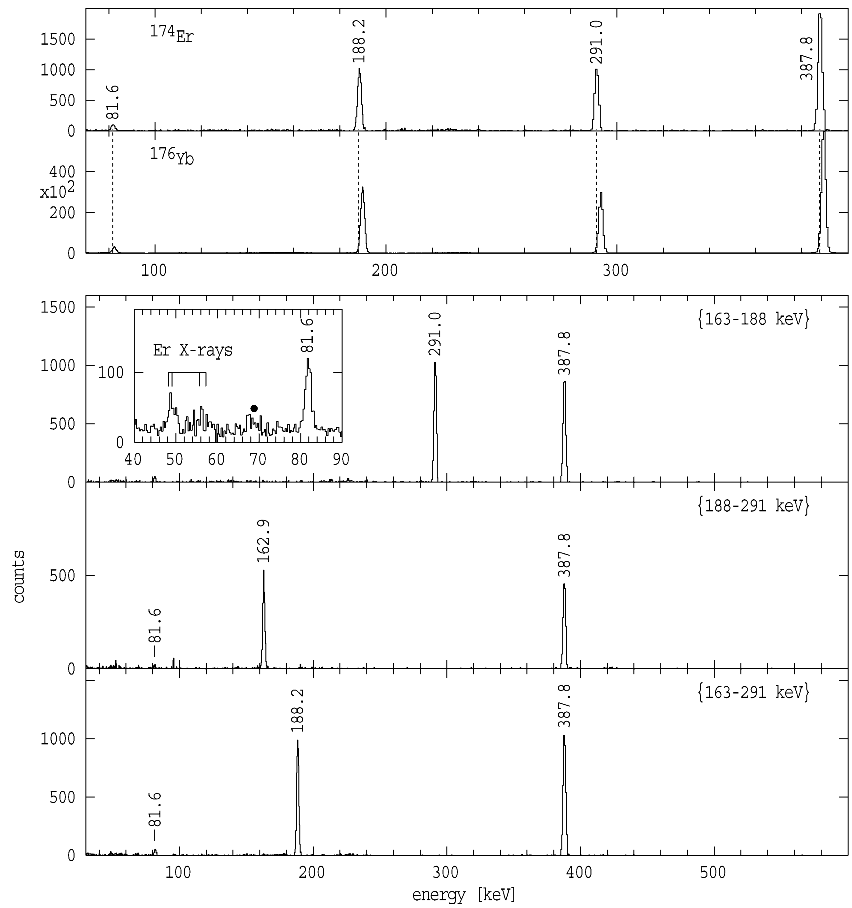

Fig. 1. Comparison of triple coincidence spectra in the out-of-beam time period, with coincidence gates as indicated. The inset shows a detail in the X-ray energy region of the sum of several spectra. The upper pair of panels compares a sum of double gates with the 163 keV transition with the equivalent set for the 96 keV transition in ^{176}Yb, to illustrate the difference in transition energies. (Note the different energy scales.) Contaminants are indicated by filled circles.

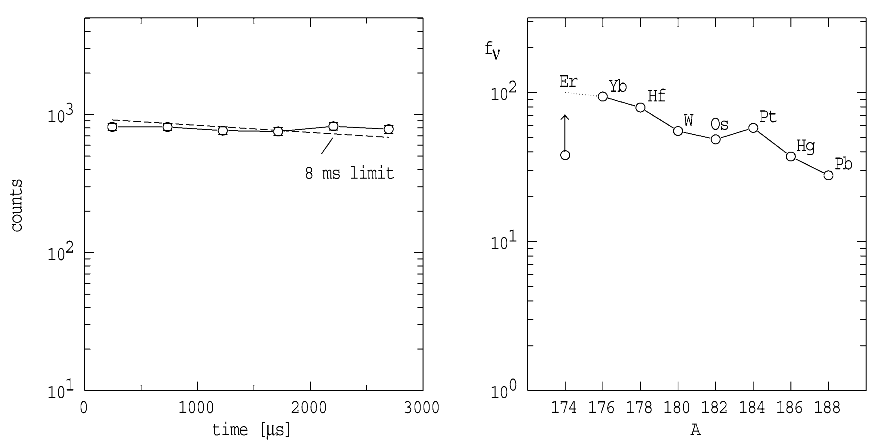

Fig. 2. Coincidence intensities of γ-rays in the decay of the 8^- isomer in ^{174}Er as a function of time after the beam pulse, in the (1 ms)/(3 ms) chopped beam experiment (left panel) and reduced hindrances for the E1 decays from the 8^- isomers in the $N = 106$ isotones (right panel). Note that the point for ^{174}Er is a limit.

factor of 10^3–10^4 often arbitrarily used in the evaluation of reduced hindrances for E1 transitions.) The naive expectation from the systematics is that ^{174}Er would have $f_\nu \sim 100$, which would result in a meanlife of ∼7 s for the 8^- isomer, well outside the range of the present measurements.

Considering the energy systematics (Fig. 3), it is remarkable that the isomer occurs from essentially the middle of the neutron shell in the neutron-rich nuclide ^{174}Er, in all well-deformed isotones up to Os, through the transitional region (^{184}Pt), into the region of oblate–prolate shape coexistence (^{186}Hg) and finally in the very neutron-deficient isotope ^{188}Pb, where its presence has been taken as evidence for a prolate sub-minimum in a nucleus which exhibits triple shape coexistence [14]. The robust nature of the configuration is only disturbed in ^{178}Hf where

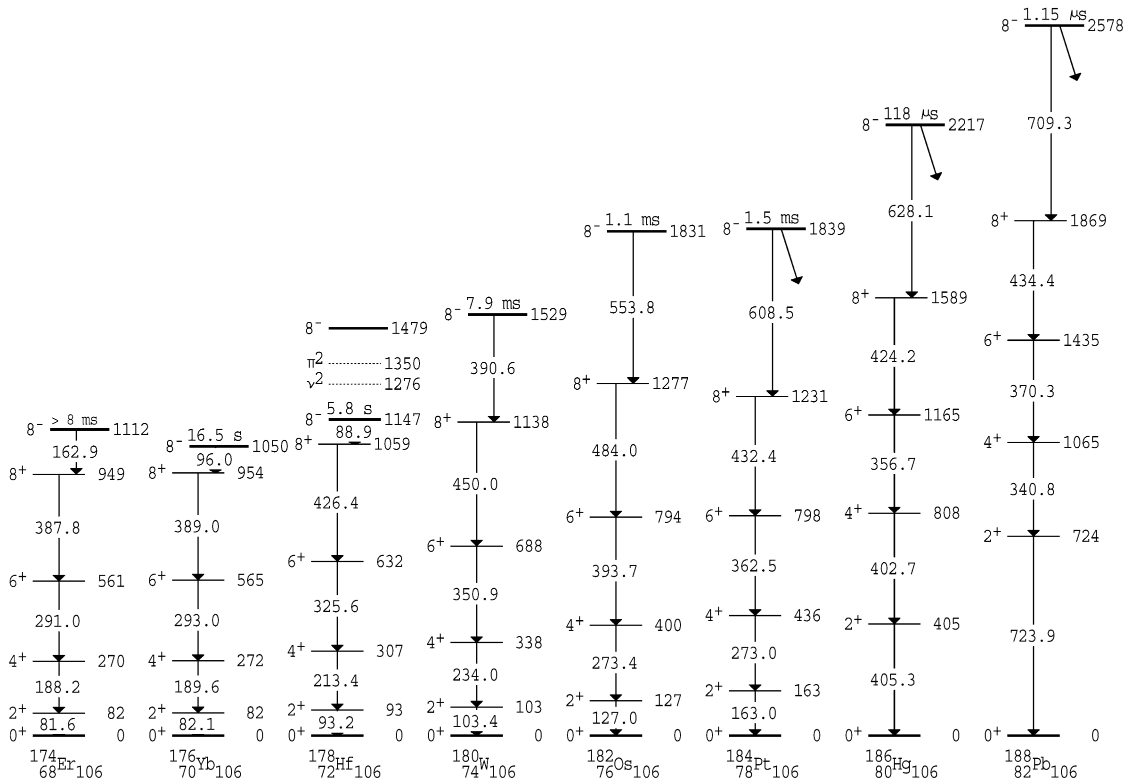

Fig. 3. Proposed level scheme for ^{174}Er and level systematics for the $N = 106$ isotones. Note that two 8^- states occur in ^{178}Hf because of an alternative 2-quasi-proton configuration, resulting in mixing. The unperturbed levels deduced previously are shown by dashed lines in that case. As indicated by the diagonal arrows, additional branches occur in ^{186}Hg and ^{188}Pb.

strong mixing occurs with an alternative 8^- state from the two-quasiproton configuration $\pi^2\, 7/2^+[404] \otimes 9/2^-[514]$, with the result that the lower experimental state is strongly mixed, being $64\%\nu^2 + 36\%\pi^2$ [15–17]. (The mixing also has an effect on the reduced hindrances for the E1 decays [18].)

In the $N = 104$ isotones, the equivalent 8^- intrinsic state generally does not compete with the favoured $\nu^2\, 7/2^-[514] \otimes 5/2^-[512]$; $K^\pi = 6^+$ configuration. The γ-decay of the yrast sequence in ^{172}Er had been identified previously from multinucleon transfer reactions, but no isomers were known [2]. We have observed delayed feeding into this sequence via a 970 keV transition, establishing, incidentally, more precise energies for the ground-state band sequence. The isomer is relatively long-lived, at least several microseconds, but is too weakly populated to allow us to extract a more definitive limit. Its population is consistent with 2-proton, 2-neutron transfer from ^{176}Yb and it is also observed relatively more strongly in the measurements with the ^{174}Yb target. Part of the population in the ^{176}Yb experiment may also be due to 2-proton transfer from the residual ($\sim$2%) ^{174}Yb in the enriched ^{176}Yb target. As in the systematics for the 8^- isomers in the $N = 106$ isotones, an alternative 6^+ two-proton configuration occurs in the Hf case (see Fig. 4), with the unperturbed two-proton state being lower in this case (as indicated by the dashed line), resulting in the dominance of the two-proton component in the lower experimental state.

Considering the branching in ^{172}Er, only the 970 keV branch to the 6^+ state was observed, which is consistent with the decay pattern in ^{174}Yb where the transition to the 6^+ state is the strongest branch. Because of the low statistics we cannot place a stringent limit on a possible E2 transition of 1245 keV to the 4^+ state, which, together with the lifetime, is of some interest since the E2 branch in ^{174}Yb is very inhibited and has not been satisfactorily explained [10].

In this context it is worth noting that it has been proposed [19] that, the as yet unidentified, $Z = 66$ isotone ^{170}Dy may have a particularly long-lived 6^+ isomer if an extrapolation of hindrances from ^{174}Yb on the basis of an increase in the valence-particle parameter $N_p N_n$ were valid. The ^{172}Er case, while having a slightly lower value of $N_p N_n$ than ^{170}Dy (308 rather than 352), may now be more accessible experimentally given identification of the excitation energy and decay in the present work.

Configuration-constrained potential energy surface (PES) calculations for the two-quasineutron 8^- configurations incorporating a non-axial deformed Woods–Saxon potential and Lipkin–Nogami pairing were reported by Xu et al. [20] for the $N = 106$ isotones from $Z = 70$ (Yb) to $Z = 82$ (Pb), in fact before the experimental observation of the 8^- isomer in ^{188}Pb [14], resulting in agreement with experiment of 20–150 keV. Calculations carried out with equivalent parameters for ^{174}Er in the present work give a value of 1120 keV, very close to the observed energy of 1112 keV, however, this is to some extent fortuitous since the experimental and theoretical values for ^{176}Yb differ by about 90 keV [20]. Since the two neutron orbitals involved are close to the Fermi surface and not strongly

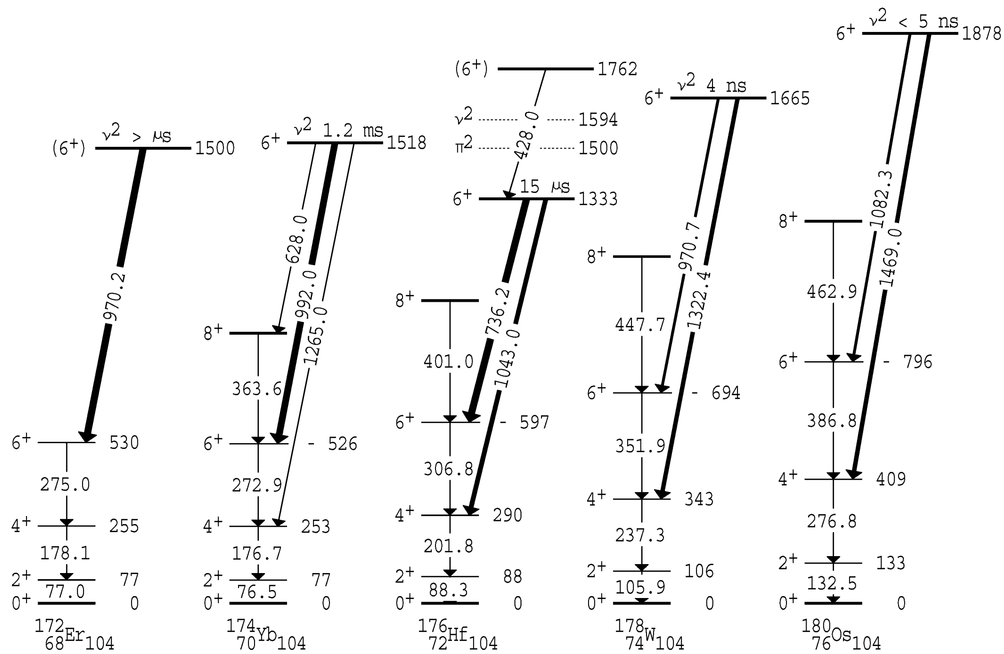

Fig. 4. Proposed isomeric decay in ^{172}Er compared to the known 6^+ decays in the isotones ^{174}Yb, ^{176}Hf, ^{178}W, and ^{180}Os.

dependent on the deformation, the main controlling factor is, in fact, the neutron pairing strength G_n.

Similar PES calculations have also been reported [19] for the ground state of ^{172}Er and in the present case, these have been extended to calculate specifically the 6^+ intrinsic states in the $N = 104$ isotones.

The excitation energy results for both 6^+ and 8^-, 2-quasi-neutron states are given in Table 1, including the previously calculated 8^- cases from Ref. [20]. These have been calculated using values of G_n deduced from the experimental masses except for the ^{172}Er and ^{174}Er cases where extrapolated masses have had to be used [21]. The predicted deformations for the ground states of ^{172}Er and ^{174}Er are very similar with $\beta_2 = 0.279$, $\beta_4 = -0.038$, and $\beta_2 = 0.284$, $\beta_4 = -0.023$, respectively. No significant difference in deformation is predicted between the 6^+ and 8^- intrinsic states and their respective ground states. Inspection of the new level schemes shows that the transition energies in yrast bands of ^{174}Er and ^{176}Yb are very similar, as are the corresponding sequences in the ^{172}Er and ^{174}Yb pair, consistent with saturation of the deformation near mid-shell. Furthermore, the experimental E_{4^+}/E_{2^+} ratios are essentially identical for the $N = 104$ and $N = 106$ isotones with $Z = 68$, 70 and 72.

As can be seen from the table, the predicted excitation energies of the two-quasiparticle states are in reasonable agreement with the experimental values ($E_{\text{exp.}}$), given that residual spin–spin interactions are not included in the calculations and the pairing strengths deduced from averaged mass-differences are not *necessarily* appropriate for the calculation of excitation energies in a specific nucleus. There has been extensive evaluation of the pairing gaps and their relationship to various mass-difference formulae [22] and there is continuing debate about the subtle effects contributing to the observed odd–even staggering (see, for example, [22–24]).

Focussing instead on the need for parameters appropriate for the calculation of the excitation energies of multi-quasiparticle states in neutron-rich nuclei, the approach taken here has been to adjust the value of G_n to reproduce the experimental values, after correction for the spin–spin interactions. The latter are estimated to be about −93 keV (attractive) in the 8^- configuration and −128 keV in the 6^+ configuration, and the same values have been used for each isotope. The corrected experimental energies are given as $E^{\text{unp.}}_{\text{exp.}}$ in the table. (Note that the interaction values used differ somewhat from those in the compilation of ν–ν interactions in Ref. [26] because of a re-evaluation by Kondev [27] of some of the empirical values.)

Since the required value of G_n will also depend on the extent of the configuration space used, for consistency the prescription [28] of taking approximately $\sqrt{15N}$ levels above and below the Fermi surface has been used. Specifically this translates to the use of a total of 86 levels in the $N = 106$ cases and 84 levels in the $N = 104$ cases. Various values of G_n are compared in Table 1. Those labelled [I] are from the formula

$$G_n = \left[18.95 - 0.078(N - Z)\right]/A$$

given by Dudek, Majhofer and Skalski [25], and list-[II] gives those extracted by reproducing the odd–even mass differences. List-[III] contains the values of G_n required to *reproduce* the unperturbed excitation energies. The same values are plotted in Fig. 5.

It is clear that the mass-dependent formula that is sometimes used in multi-quasiparticle calculations, does not follow the local variation suggested by the mass differences. Furthermore, in the $N = 106$ cases, while the values required to reproduce experiment ([III]) differ in detail from the mass-difference values ([II]), they do show a similar trend. In sharp contrast to this comparison, the values of G_n required to reproduce experiment in the $N = 104$ cases differ markedly from the mass-difference

Table 1
Excitation energies from experiment and potential-energy surface calculations for the 8^- and 6^+ isomers in the deformed $N = 106$ and $N = 104$ isotones, and the neutron-pairing strengths G_n from different approaches

J^π	Nuclide	$E_{\text{exp.}}$ (keV)	$E^{\text{unp.}}_{\text{exp.}}$ (keV)	$E_{\text{theor.}}$ (keV)	Ref.	G_n (keV)[1]		
						[I]	[II]	[II]
8^-	^{174}Er	1112	1205	1120	this work	91.87	(87.5)	89.4
	^{176}Yb	1050	1143	1140	[20]	91.70	87.7	88.5
	^{178}Hf	*1276*[2]	*1369*	1320	[20]	91.56	91.2	92.0
	^{180}W	1529	1622	1560	[20]	91.40	93.9	94.3
	^{182}Os	1831	1924	1760	[20]	91.26	94.9	97.4
	^{184}Pt	1839	1932	1885	[20]	91.10	97.5	98.1
6^+	^{172}Er	1500	1628	1343	this work	93.8	(89.7)	96.3
	^{174}Yb	1518	1646	1305	this work	93.7	89.6	96.5
	^{176}Hf	*1594*[3]	*1722*	1462	this work	93.5	93.2	98.2
	^{178}W	1665	1793	1765	this work	93.3	96.4	96.8
	^{180}Os	1878	2006	1967	this work	93.1	97.0	97.6

[1] Values listed under [I] are from the formula of Ref. [25], [II] are values adjusted to the odd–even mass differences extracted from the five-point formula except for the ^{172}Er and ^{174}Er cases; [III] are the values extracted by reproducing the 2-quasiparticle energies.
[2] Energy corrected for mixing as given in Fig. 3.
[3] Energy corrected for mixing as given in Fig. 4.

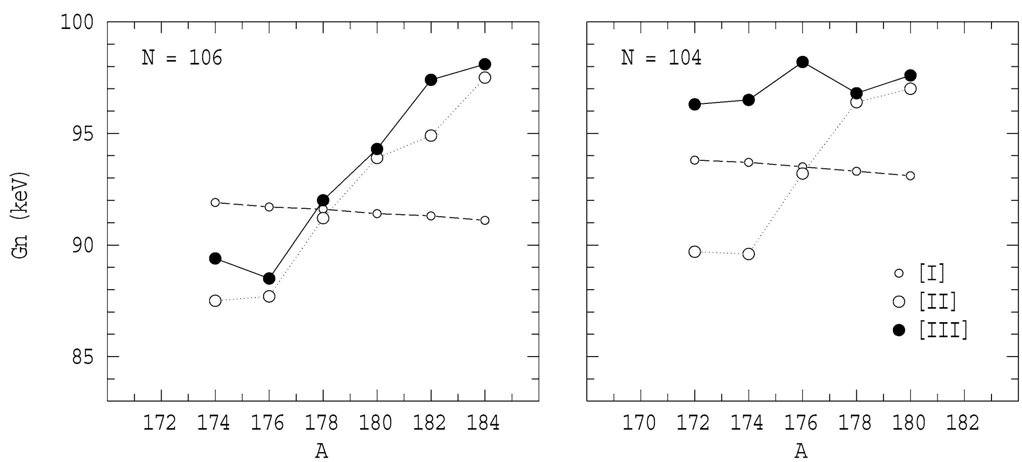

Fig. 5. Values of the pairing strength parameter G_n for the $N = 104$ and $N = 106$ isotones from three different prescriptions as listed in Table 1.

values for all cases below $Z = 74$. While this could be partly due to uncertainties in the calculated deformations and precise level spacings, the differences are substantial as can be seen from Table 1, and correspond to underestimates of ∼300 keV in excitation energy. Since the two orbitals involved in the 6^+ excitation are those closest to the Fermi surface and neither has a large slope with respect to deformation, it seems unlikely that deformation uncertainties can explain the difference. As stated earlier, the experimental properties such as transition energies and E_{4^+}/E_{2^+} ratios all imply very similar deformations, consistent with predictions. The fact that the pairing strengths required in the 8^- cases are not very different from those estimated from mass-differences, and the trends of the mass-difference values are similar in both isotonic sequences, adds to the difficulty in understanding this result. Independent of the cause, the values of the pairing strength extracted will have a very significant impact on the predictions for higher-seniority multi-quasiparticle states in this neutron-rich region. Identification of higher-seniority states in neutron-rich cases may provide a test of the validity of the pairing strengths extracted.

In summary, a long-lived isomer has been identified in the neutron-rich nucleus ^{174}Er exposing its previously unknown yrast sequence and completing a sequence of isomers in the $N = 106$ isotones arising from the $\nu^2\, 7/2^-[514] \otimes 9/2^+[624]$ configuration, from $Z = 68$ to $Z = 82$. It is unlikely that this sequence will be easily extended since of the isotones at each extremity, $^{172}_{66}$Dy is probably out-of-reach of current techniques and while structure in $^{190}_{84}$Po has been identified [29], this is another case of shape coexistence where two-quasiparticle excitations within the prolate minimum in the potential well are likely to be non-yrast and, therefore, weakly populated. A candidate for the $\nu^2\, 7/2^-[514] \otimes 5/2^-[512]$, 6^+ isomer in ^{172}Er has also been identified. Constraints on the neutron-pairing strength independent of masses have been obtained by reproducing the excitation energies of the 6^+ and 8^- isomers. There is a very marked discrepancy for the pairing strengths deduced in this way for the $N = 104$ cases, that remains to be explained. Further experimental studies are also required to define the lifetimes of the isomers now established in ^{172}Er and ^{174}Er.

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